

Brief Report

Quantifying Fire Behavior Prediction Uncertainty Associated with User-Defined Variables in WFDS

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Abstract

Coupled fire–atmosphere models (CFAMs) are increasingly proposed as an important tool for investigating a range of scientific and management questions, including the design of fuel management strategies. Uncertainty in CFAM outputs arises from environmental and fuel inputs, and a host of user-defined simulation choices such as fire approach angle and ignition timing. In this study, we used the Wildland–Urban Interface Fire Dynamics Simulator (WFDS) to quantify uncertainty in rate of spread and canopy consumption across pre- and post-restoration ponderosa pine stands. Two ensembles were conducted: (1) varying fire approach angles across 12 rotations and (2) varying ignition time in 80 simulations (five per plot, with 0 s delay, 250 s delay, and three random intervals in between). Metrics evaluated were rate of spread and percent canopy consumption. Variability was quantified using coefficients of variation (CVs). Approach-angle variation produced a mean CV of 5.46% for rate of spread, with treated stands exhibiting reduced variability relative to untreated stands. Canopy consumption showed a mean CV of 6.16%, with treatment having no effect. Ignition-time variation produced smaller CVs (rate of spread: 2.47%; canopy consumption: 3.60%) with no differences between management conditions. These results indicate that user-defined configuration choices contribute measurable but modest uncertainty, and that structural modifications from management can reduce sensitivity of fire spread. Incorporating these sources of uncertainty into formal frameworks will improve interpretation of CFAM outputs for operational and research applications.

Keywords: wildfire modeling; uncertainty quantification; fire behavior; VVUQ; WFDS; user-defined variables



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1. Introduction

Coupled fire–atmosphere models (CFAMs) are increasingly proposed as an effective tool to investigate fire behavior and fire–atmosphere interactions across a range of wild-land fire applications. Examples of CFAMs include FIRETEC [1], the Wildland–Urban Interface Fire Dynamics Simulator (WFDS) [2], QUIC-Fire [3], FireStar [4], WRF-Fire [5], and MesoNH-ForeFire [6]. Several studies have applied CFAMs to assess the design and effectiveness of fuel treatments and prescribed burns [7–10]. As the use of CFAMs has expanded, there has been increased emphasis on evaluating model credibility and limitations using Verification, Validation, and Uncertainty Quantification (VVUQ) frameworks [11,12].

VVUQ frameworks have been established to evaluate modeling systems across a wide range of scientific disciplines, including aerospace, climate science, and engineering [13–16].

Within these frameworks, verification evaluates the correctness of the numerical implementation and solution of the governing mathematical equations, while validation assesses the degree to which model outputs represent the relevant physical system for their intended use. Uncertainty quantification (UQ) seeks to identify, propagate, and characterize all relevant sources of uncertainty affecting a specified quantity of interest. Together, verification, validation, and uncertainty quantification provide the foundation for establishing model credibility and building confidence in simulation results.

Coupled fire–atmosphere models have benefited from substantial efforts in verification and validation, particularly through idealized and small-scale experimental studies. Examples include code verification and sensitivity testing using simplified configurations [1,17], validation against laboratory-scale or prescribed burn experiments such as FireFlux, RxCADRE, and other well-instrumented field campaigns [18–21]. These studies have increased confidence in the model with respect to fire spread, plume dynamics, and fire–atmosphere interactions under controlled conditions.

Comprehensive UQ associated with CFAMs has received comparatively limited attention relative to verification and validation in wildland fire modeling. Uncertainty in fire behavior predictions arises from multiple sources, including the parametrizations of the fuel complex and burning conditions, the model structure, and a host of user-defined choices associated with unknown parameters, assumptions, and workflows that support design and execution of a numerical experiment. Several previous studies have utilized sensitivity analyses, a branch of UQ that studies model output dependency on inputs, to investigate uncertainty related to specific properties of the fuel complex, wind fields, and ignition patterns associated with prescribed burns [9,22–25]. These studies have shown that predicted rates of spread and canopy consumption are especially sensitive to the amount and distribution of surface and canopy fuels as well as the burning conditions [10,26]. While sensitivity analyses identify which inputs have the greatest relative influence on model predictions, they do not quantify the overall uncertainty associated with the application of a given model. Valero et al. [27] used a multi-fidelity uncertainty propagation framework with WFDS to evaluate uncertainty stemming from fuel and weather parameters on rate of spread in grasslands. Their results indicate that uncertainty in WFDS was primarily driven by fuel moisture fraction, the fine fuel load, and wind speed. To our knowledge, this represents the first application of a formal uncertainty quantification framework to a CFAM.

In addition to uncertainties associated with fuels and burning conditions, CFAM simulations also require numerous user-defined choices. These include decisions such as computational grid resolution, domain size, ignition geometry, ignition timing, fire approach angle, and simulation duration. These choices are often selected during the design stage of the study to satisfy the objectives or due to computational constraints. Although some user-defined choices may be constrained by observations in fire reconstruction or validation studies, these choices are often not uniquely prescribed in simulations designed to investigate general fire behavior or compare management scenarios. In these applications, multiple configurations or parameter estimates may be equally reasonable or justifiable for addressing a given research question. Although some user-defined choices, such as grid resolution and domain size, are routinely evaluated through numerical sensitivity or convergence analyses [28,29], comparatively little attention has been given to quantifying the uncertainty introduced by choices that are not uniquely constrained or measurable. For example, Benali et al. [30] found that fire rate of spread varied significantly in response to both the ignition configuration and fire approach angle with FARSITE [31]. Similarly, Jonko et al. [32] found that perturbations in ignition timing under marginal burning conditions altered predicted burned area by more than 400%. Together, these studies demonstrate

that fire approach angle and ignition timing can influence simulated fire behavior when explicitly varied. However, because these variables are often fixed to isolate other processes in CFAM studies [33,34], the uncertainty introduced by those choices has received comparatively little attention, particularly in simulation scenarios where they are not the focal interest of the study.

In this study, we assessed the uncertainty introduced by two user-defined choices, approach angle and ignition timing, on predicted rate of spread and canopy consumption using WFDS (V9977). We performed two ensembles of simulations parametrized with data representing pre- and post-restoration treatment stand structures in ponderosa pine-dominated forests. All simulations were performed using a single wind speed and surface and crown fuel moistures, representing a moderate wildfire condition.

2. Materials and Methods

Fire spread and canopy consumption were simulated for two ensembles using WFDS Version 9977. The first ensemble varied fire approach angle for eight plots across 2 treatment statuses and 12 rotations ($n = 192$). The rotations were done in 30-degree increments, with the purpose of having 12 rotations representing the entire range of approach angles. The second ensemble varied ignition time between 0 and 250 s on 16 plots: one with zero delay, one with 250 s delay, and three with randomly selected delays between 0 and 250 s ($n = 80$), which includes a range of justifiable ignition timings matching the use of WFDS in the literature [33,34]. Alterations in the ignition delay time conceptually introduce variability in the turbulent wind field and thus in the development of the wildland fire, while variations in approach angle represent a combination of differences in fuel arrangement and the wind field.

Simulations were parameterized using stem map data from eight 4-ha ponderosa pine (*Pinus ponderosa*) plots for both pre- and post-treatment across the Colorado Plateau and southern Rocky Mountains [35,36]. Data collection occurred from June through early August of 2012 and 2013, with all trees at least 1.37 m tall being recorded. Datasets contained tree location, height, diameter at breast height, crown radius, and crown base height. Forest management actions aimed to create a mosaic of individual trees, as well as various-sized tree clumps and openings. Tree crowns were modeled as circular cones with properties of a surface area/volume ratio of 4000 m^{-1} [37], bulk density of 1.2 kg m^{-3} , drag constant of 0.125, and foliage moisture of 100%. All simulations used a consistent homogeneous surface fuel layer with a bulk density of 1 kg m^{-3} , height of 8 cm, and fuel moisture of 8%, matching the use of the stem-plot data used in [33]. These fuel data were used to capture a wide range of realistic forest structures ranging from areas characterized by dense forests with high crown fire potential to recently treated forests.

The spatial configuration for each WFDS simulation consisted of three components: a populated fuels domain, a simulation domain, and an area of interest (AOI) nested within the simulation domain (Figure 1a). The populated fuels domain represented the largest extent of forest fuels considered and provided the reference landscape for all simulations. Within the populated fuels domain was the simulation domain, which measured $1050 \text{ m} \times 400 \text{ m} \times 160 \text{ m}$ and defined the active computational region used for fire spread simulations. To vary fire approach angle, the simulation domain was rotated within the populated fuels domain while maintaining a constant wind direction (Figure 1b). The AOI measured $200 \text{ m} \times 200 \text{ m}$ and extended from $x = 700\text{--}900 \text{ m}$ and $y = 100\text{--}300 \text{ m}$ within the simulation domain. Fire behavior metrics, including rate of spread and canopy consumption, were calculated only within the AOI. The AOI was positioned downwind of the ignition line to allow fire spread to develop prior to entering the analysis region

and to reduce ignition-related model artefacts. The AOI was discretized using $1\text{ m} \times 1\text{ m}$ horizontal grid cells, while the remainder of the simulation domain used $2\text{ m} \times 2\text{ m}$ cells.

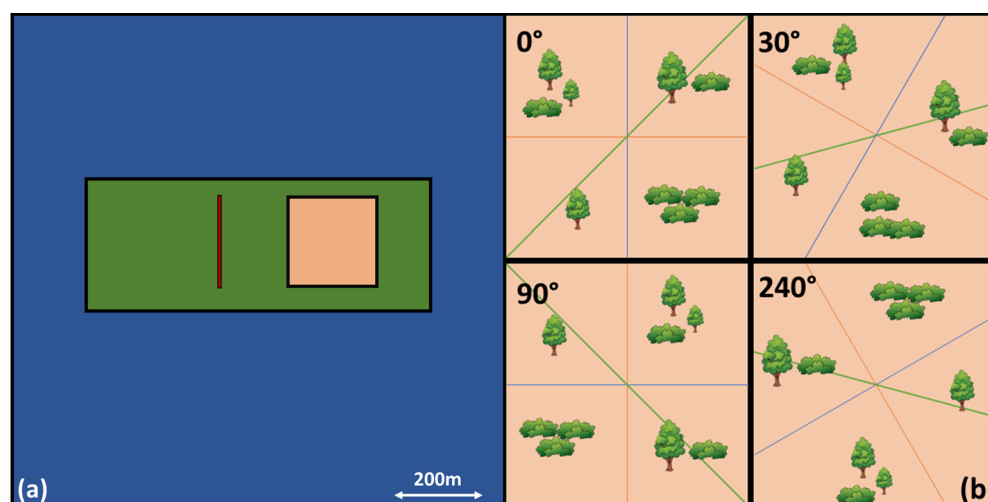


Figure 1. Simulation domain schematic for WFDS runs. (a) The populated fuels domain (blue) contained the rotatable simulation domain (green), area of interest (AOI; salmon), and ignition line (red), where fire behavior metrics were calculated. (b) Example rotations of the simulation domain used to generate different fire approach angles relative to the fixed fuels landscape.

For all simulations, wind entered the western boundary as a power-law profile with a reference wind speed of 5 m s^{-1} at 10 m above ground level. Fires were initiated using a $2\text{ m} \times 280\text{ m}$ ignition line with the southwest corner located at $x = 400\text{ m}$ and $y = 60\text{ m}$. Ignition was represented as a burner with a heat release rate of 600 kW m^{-2} starting at 250 s and applied for 80 s. Ignition-time variation for the second ensemble was implemented by adding a delay to the 250 s starting time, ranging from 250 to 500 s.

For all simulations, we calculated rate of spread (ROS) and percent canopy consumption within the AOI. Rate of spread was derived from using fire time-of-arrival outputs along the wind direction. Specifically, we determined the time at which fire first reached the upwind boundary of the AOI and the time at which it reached the downwind boundary. ROS was then calculated as the length of the AOI in the wind-aligned direction divided by the difference between these two arrival times, yielding a forward ROS (m s^{-1}) across the AOI. Percent canopy consumption was calculated as the fractional loss of pre-burn canopy biomass. Coefficients of variation (CV) were calculated for all rotations or ignition-time variations and compared between pre- and post-restoration stands using *t*-tests. For all significance tests, we used an α of 0.05. All analyses were performed in R [38].

3. Results

For simulations varying fire approach angle, mean plot-wise rate of spread ranged from 0.46 to 0.77 m s^{-1} , while mean canopy consumption ranged from 46% to 89% (Table 1). The mean coefficient of variation (CV) for ROS across all sites was 6.17% ($\sigma = 3.41$, 95% CI: 4.35–7.98%) (Figure 2). Untreated stands exhibited significantly greater uncertainty than treated stands in ROS (8.37% vs. 3.97%; $t = 3.89$, $p < 0.01$) (Figure 3). In contrast, canopy consumption exhibited a mean CV of 6.29% ($\sigma = 4.02$, 95% CI: 4.15–8.44%), with no significant difference between untreated and treated stands ($t = 0.29$, $p = 0.78$).

Table 1. Mean, standard deviation (σ), and 95% confidence intervals (95% CI) for rate of spread (ROS), coefficient of variation of rate of spread (CV_{ROS}), canopy consumption (CC), and coefficient of variation of canopy consumption (CV_{CC}) for simulations varying fire approach angle and ignition timing under untreated (pre-restoration), treated (post-restoration), and combined.

		Approach Angle			Ignition Timing		
		All	Pre	Post	All	Pre	Post
ROS-(m/s)	Mean	0.577	0.633	0.521	0.537	0.583	0.491
	SD	0.095	0.094	0.056	0.075	0.076	0.038
	95% CI	0.526–0.627	0.555–0.712	0.474–0.567	0.498–0.577	0.519–0.646	0.459–0.522
CV_{ROS} -(%)	Mean	6.17	8.37	3.97	2.47	3.34	1.60
	SD	3.41	3.58	1.01	2.46	3.31	0.53
	95% CI	4.35–7.98	5.37–11.4	3.12–4.82	1.16–3.78	0.57–6.10	1.16–2.04
CC-(%)	Mean	62.8	69.7	56.0	64.3	70.5	58.0
	SD	15.8	13.2	15.8	13.7	11.1	13.9
	95% CI	54.5–71.3	58.7–80.7	42.8–69.2	56.9–71.6	61.2–79.8	46.4–69.5
CV_{CC} -(%)	Mean	6.29	6.54	6.05	3.60	2.70	4.51
	SD	4.02	3.67	4.59	2.30	1.32	2.78
	95% CI	4.15–8.44	3.47–9.61	2.22–9.88	2.38–4.83	1.60–3.81	2.18–6.83

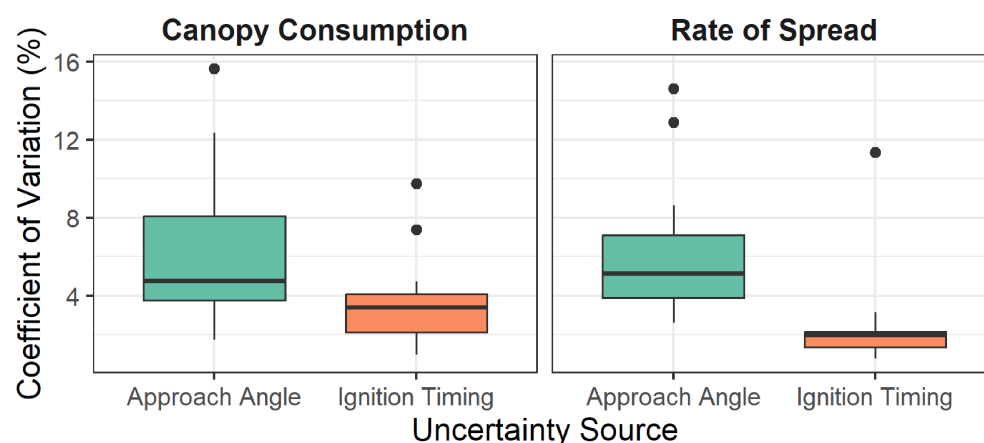


Figure 2. Uncertainty in percent canopy consumption and rate of spread (ROS) for approach-angle ensemble and ignition-time ensemble. Horizontal lines indicate median values, boxes indicate interquartile ranges, and whiskers show the full range.

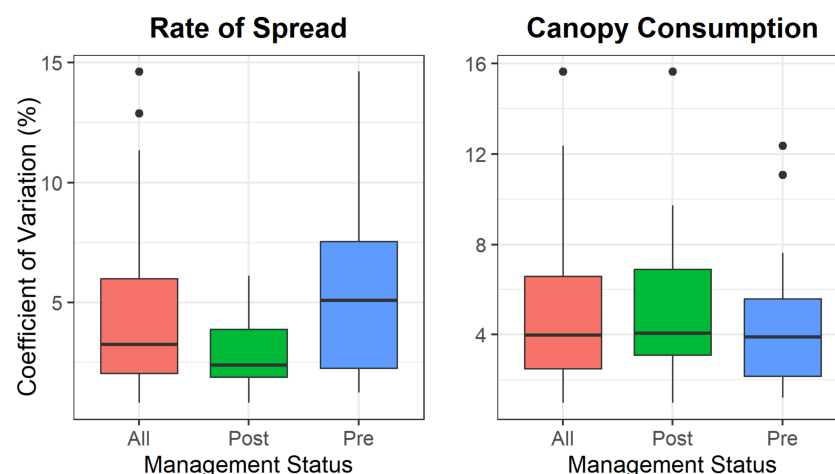


Figure 3. CVs for rate of spread and canopy consumption are shown for pre- (untreated) and post-restoration (treated) plots for the approach angle ensemble.

For simulations varying ignition timing, mean plot-wise rate of spread ranged from 0.45 to 0.71 m s⁻¹, while mean canopy consumption ranged from 39% to 88% (Table 1). The mean CV for ROS was 2.47% ($\sigma = 2.46$, 95% CI: 1.16–3.78%) (Figure 2), with no significant difference between untreated and treated stands ($t = -1.46$, $p = 0.14$). Likewise, canopy consumption exhibited a mean CV of 3.60% ($\sigma = 2.30$, 95% CI: 2.38–4.83%), with no significant treatment effect ($t = 1.66$, $p = 0.12$).

Overall, both user-defined variables contributed modestly to variability in fire behavior metrics. Management treatments reduced uncertainty in rate of spread for simulations varying approach angles but had little influence on canopy consumption (Figure 3). Ignition-time variation introduced smaller uncertainty than approach angle, and this effect did not differ between treated and untreated stands. Although the observed differences in rate-of-spread variability are statistically significant, their magnitude is unlikely to alter interpretation of previous CFAM studies evaluating treatment effects under a fixed approach-angle assumption.

4. Discussions

The results indicate that variability in fire approach angle introduces a measurable, though relatively modest (3–8%), contribution to uncertainty in rate of spread and canopy consumption. Our uncertainty estimates are much smaller than those of previous studies, which have shown uncertainties of 20–35% for comparable ensembles [10,32]. The difference between the relatively small uncertainty in our findings compared to that of previous studies likely arises through two mechanisms: experimental design choices and burning conditions. Both Atchley et al. [10] and Jonko et al. [32] assessed fire behavior immediately after fire ignition occurred, while we included a fire development zone in between the ignition line and the area of interest. The inclusion of a fire development zone is commonly used [2,9,33] with the express purpose of minimizing the effect of ignition design choices on predicted fire behavior. Another source of difference between our study and Atchley et al. [10] and Jonko et al. [32] was related to the range of burning conditions evaluated. Although our simulations captured a range of fuel conditions, the burning conditions were set to represent moderate wildfire conditions in the western US, whereas Atchley et al. [10] and Jonko et al. [32] utilized conditions representative of more marginal fire behavior. Under marginal conditions, it is reasonable to expect small perturbations to have large impacts and thus introduce more uncertainty in predicted fire behavior. Our results contribute to a growing body of literature that suggests that uncertainty associated with user-defined choices (such as fire approach angle) depends upon complex interactions between simulation design and the physical conditions being modeled. Developing comprehensive uncertainty quantification frameworks for CFAMs will therefore require evaluating multiple sources of uncertainty simultaneously, including physical inputs, model parameterizations, and user-defined simulation choices.

Differences in ROS uncertainties between treated and untreated stands suggest that model uncertainty also arises from variations in the local fuels complex. More specifically, we found that treated stands, characterized by reduced tree density and fewer ladder fuels, exhibited lower variability in rate of spread across approach angles. In contrast, untreated stands had greater variability; visual assessment of the simulations suggests that this uncertainty is associated with infrequent alignment between the gaps in the overstory fuels and wind flow, leading to increased rates of fire spread. While this effect can occur in both treated and untreated forests, the denser canopy and infrequent gaps associated with untreated forests lead to this phenomenon occurring less often and thus contributing to greater uncertainty. Canopy consumption, however, showed no detectable difference in uncertainty between management conditions. Unlike rate of spread, which is

sensitive to both local and large-scale interactions between the fuels and wind flow, canopy consumption is primarily dependent on local-scale horizontal and vertical continuity [34]. Our rotation methodology conserved both the horizontal and vertical continuity of the canopy, only changing its orientation relative to the wind. Therefore, the canopy structure, which controls canopy consumption, remained largely unchanged as the domain was rotated. As a result, varying fire approach angles introduced little uncertainty in canopy consumption even though it had a measurable difference in uncertainty associated with the rate of spread.

Ignition-time variation produced smaller predictive uncertainty than approach angle, with mean CVs of 2.47% for rate of spread and 3.60% for canopy consumption. No significant differences were observed between pre- and post-restoration stands for either metric, indicating that ignition timing had a small effect under the development-zone conditions used in these simulations. The comparatively low uncertainty was likely influenced by the experimental design. Since our ignition line was located a substantial distance upwind of the AOI, fires developed and propagated through the fire development zone prior to entering the analysis region, reducing the influence of ignition effects on rate of spread and canopy consumption. The uncertainty associated with ignition timing is thus likely driven by turbulent flow development between the inflow boundary and the ignition line, which are likely smaller than the highly turbulent conditions used in previous studies such as Jonko et al. [32]. Under these low wind speed conditions, the observed variability may represent an approximate lower bound on run-to-run uncertainty associated with a WFDS simulation, independent of larger perturbations in fuels, wind, or ignition parametrization.

We made several assumptions in this study—homogeneous surface fuels, a single wind and moisture condition, a single ecosystem, and the use of flat terrain. Our simulations were conducted in a moderate fire scenario, with low fuel moisture and wind speed. We would not expect large changes in the range of moderate to high wildfire conditions. In high conditions, we would expect surface fuel heterogeneity to add little uncertainty as the increased flame lengths would overwhelm the fine-scale fuel variability. However, in marginal conditions, such as those used in Jonko et al. [32], we expect heterogeneous fuels and weather variables to interact to create more variability than we found here. Future studies that study uncertainty across a range of conditions are needed to confirm these expectations. We also only tested in flat terrain, which likely underestimates uncertainty under more complex topography. Slope and aspect would increase the influence of approach angle on both rate of spread and canopy consumption, as the alignment of wind direction, slope, and ladder fuels would have a large influence on crown ignition and propagation. The inclusion of a fire development zone dampened the impact of ignition-time variation, suggesting that simulations without such a zone would yield higher uncertainty. Finally, all sites were ponderosa pine forests in a limited geographic region, limiting generalization to other forest types. We would expect uncertainty to be lower for ecosystems with sparse trees or with more uniform trees.

Overall, this study demonstrates that uncertainty associated with fire approach angle and ignition timing contributes a small but non-negligible component to uncertainty in simulated fire behavior with WFDS. These results suggest that previous studies [33–35], which used similar configurations as ours, likely introduced little uncertainty into their simulations or their interpretations and conclusions. However, it is important to recognize that the magnitude of uncertainty associated with ignition timing and approach angle may depend strongly on simulation configuration, burning conditions, fuel complex, and the degree to which fires are allowed to stabilize prior to analysis.

5. Conclusions

This study quantified the uncertainty in rate of fire spread and canopy consumption introduced by two common user-defined variables in coupled fire-atmospheric models: fire approach angle and ignition timing. Our results indicate that these two variables introduced a relatively small (3–8%) uncertainty. Furthermore, we found that fuel complexes characteristic of untreated forests resulted in greater uncertainty due to approach due to fuel-fire-atmospheric interactions. Explicitly accounting for user-defined sources of uncertainty helps modelers improve the development and interpretation of studies using CFAMs. Future work that extends this framework across a broader range of fuel complexes, burning conditions, topography, and model parametrizations is needed to better understand the complex interactions between these uncertainties.

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Conflicts of Interest: Author Scott M. Ritter was employed by the company Delos Insurance Solutions. Author Justin P. Ziegler was employed by the company Aster Global Environmental Solutions. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CFAM	Coupled Fire Atmospheric Model
CV	Coefficient of Variation
ROS	Rate of spread
CC	Canopy Consumption
WFDS	Wildland Fire Dynamics Simulator

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